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# RIDE QUALITY DESIGN CRITERIA FOR AIRCRAFT WITH ACTIVE MODE CONTROL SYSTEMS

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13. ABSTRACT

Ride quality is becoming an important area of concern in the acceptability of an aircraft. This has led to considering the use of active structural mode control systems on present and future aircraft to obtain acceptable ride quality. Although ride quality criteria are available, these criteria have not included considerations of mode control system effects and performance.

This report extends the suggested criteria of reference 1 to include the effects of an active structural mode control system. It is shown how the criteria as applied to separate vertical and lateral systems may be used in the design of a single system which controls both the vertical and lateral axes simultaneously.

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# RIDE QUALITY DESIGN CRITERIA FOR AIRCRAFT WITH ACTIVE MODE CONTROL SYSTEMS

*JOHN W. RUSTENBURG*



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## FOREWORD

This report was prepared by J. W. Rustenburg, Airframe Division, Deputy for B-1, under System 139A, B-1.

The report is the result of a continuing effort to present ideas which are of concern in the design of aircraft for ride quality. The report was submitted by the author in May 1972.

The technical report has been reviewed and is approved.

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## ABSTRACT

Ride quality is becoming an area of increasing concern in the design of aircraft. This has led to considering the use of active structural mode control systems on present and future aircraft to obtain acceptable ride quality. Although ride quality criteria are available, these criteria have not included considerations of mode control system effects and performance.

This report extends the suggested criteria of Reference 1 to include the effects of an active structural mode control system. It shows how the criteria as applied to separate vertical and lateral systems may be used in the design of a single system to control both the vertical and lateral axes simultaneously.

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## SYMBOLS

| | |
|---|---|
| b | scale parameter in probability density distribution of root mean square gust velocities |
| $f(\sigma u)$ | probability density distribution of rms gust velocities |
| $F(\sigma u)$ | cumulative probability distribution of rms gust velocities |
| $\bar{H}e$ | crew task performance index $^{\text{rms error}}/_{\text{rms fps}}$ |
| P(A) | probability of occurrence of (A) |
| P(A,B) | probability of simultaneous occurrence of (A) and (B) |
| $\sigma e$ | rms task error response - rms error |
| $\sigma u$ | rms gust velocity |
| $\sigma wg$ | rms vertical gust velocity |
| $\sigma vg$ | rms lateral gust velocity |
| $\bar{A}$ | aircraft acceleration response, rms g/ rms fps |

# SECTION I

# INTRODUCTION

In Reference 1, it was postulated that crew exposure time estimates for a given effectiveness or discomfort level were influenced by the rate of exceedance of $\sigma_e$ associated with a particular aircraft. In the choice of an acceptable probability of exceedance of a comfort or effectiveness level, the inherent assumption was that the airplane response was basically determined by a single linear parameter, namely the structural system. As a consequence, the probability of a gust level exceedance was equal to the probability of exceedance of the associated ride quality comfort or effectiveness level.

Nearly all modern aircraft have a stability augmentation system. These systems are designed primarily for rigid body mode control and usually have sensor locations for minimum structural motion signals. Thus they do not significantly alter or control aircraft structural vibration modes. Although these systems have affected the overall gust response of the basic aircraft to some degree, from a practical engineering viewpoint, their influence has not been so great as to negate the validity of the inherent assumption.

Advances in the state-of-tho-art are allowing refinements of the normal stability augmentation through sensor location and shaping network modifications to provide some structural mode control. In addition, the use of active control system for the sole purpose of alleviating structural response to gust in order to obtain adequate ride quality is becoming a

reality in new designs. In fact, such systems are being considered for application to existing aircraft in the expectation that ride quality improvements may be achieved.

With an aircraft which incorporates a structural mode control system, the assumption of a direct relationship between gust input and structural response is no longer valid. This is caused by the fact that the ride quality level experienced is very much affected by a secondary system which normally exhibits a variable and nonlinear efficiency at certain gust level inputs. Because of the interaction between the gust input and ride control system performance, the probability of exceeding a certain gust level is no longer synonymous with the probability of exceeding its associated discomfort or effectiveness level. Thus it becomes necessary to evaluate and determine an acceptable probability of exceedance of a given ride comfort or effectiveness level which includes consideration of the operating characteristics of the active ride control system. It is the purpose of this report to extend the ride quality criteria of Reference 1 to include considerations of structural mode control system for ride improvement.

## SECTION II

## SYSTEM PERFORMANCE CHARACTERISTICS

Any system designed for structural mode control demonstrates certain performance limits. These limits are caused by surface deflection limits, surface rate limits, surface area, and actuator nonlinearities. The performance degradation of a canard system with the limits mentioned is illustrated in the cross plots presented in Figures 1-3. These plots relate performance as a function of gust magnitude, surface authority or maximum deflection, surface area, and surface deflection rate.

Figure 1 plots performance as a function of gust velocity with surface authority or maximum deflection as a parameter for a given surface area. Two surface authority limits are shown. The performance is poor for small gusts because of nonlinear deadband, hysteresis, and preload. Performance is poor for large gusts because of authority limits. In between the "small" and "large" gusts, the system performance is essentially linear. As surface authority increases, a larger gust is required to "break" the system out of small-amplitude nonlinearities. If surface authority is too small, the system is ineffective because of limiting effects.

Figure 2 plots surface performance as a function of gust velocity with surface area as a parameter for two surface authority limits. Figure 3 shows surface performance as a function of gust velocity with a surface rate as a parameter for a given surface area without authority

limits. It is outside the scope of the pres discussion to evaluate systems tradeoffs.

Additional details regarding tradeoff studies can be found in Reference 3. What is of interest is the general shape of the system performance curve, in particular, the reduced effectiveness at low and high gust magnitudes. These effectiveness decrements must be evaluated in light of acceptable ride quality levels.

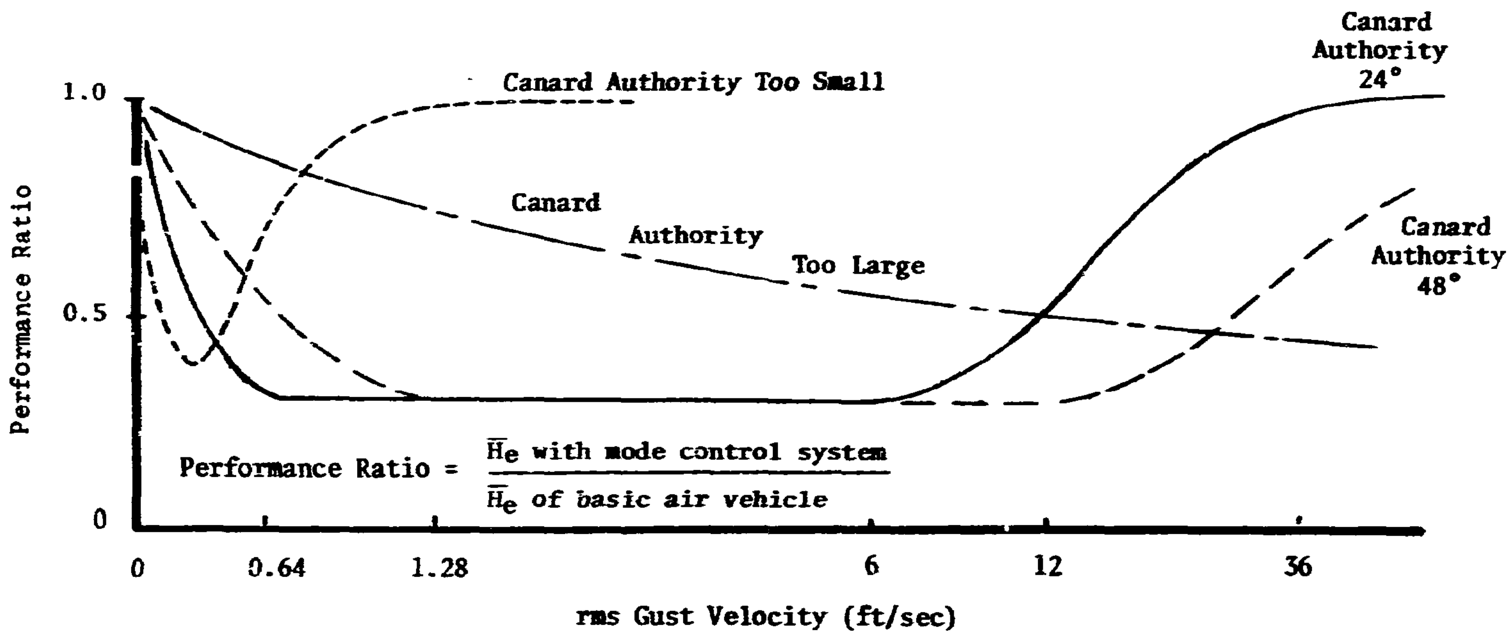


Figure 1 - SYSTEM PERFORMANCE AS FUNCTIONS OF GUST VELOCITY AND CANARD AUTHORITY

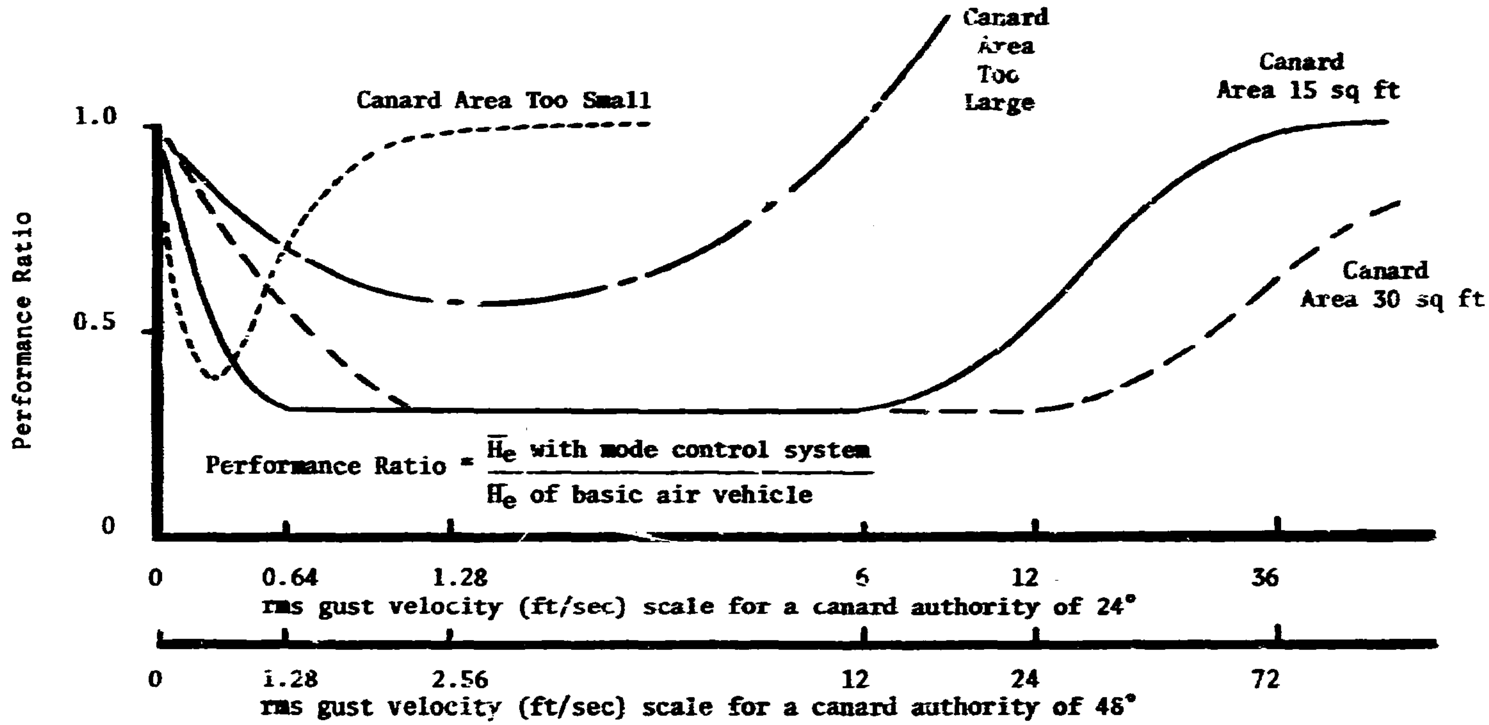


Figure 2 - SYSTEM PERFORMANCE AS FUNCTIONS OF GUST VELOCITY AND CANARD AREA

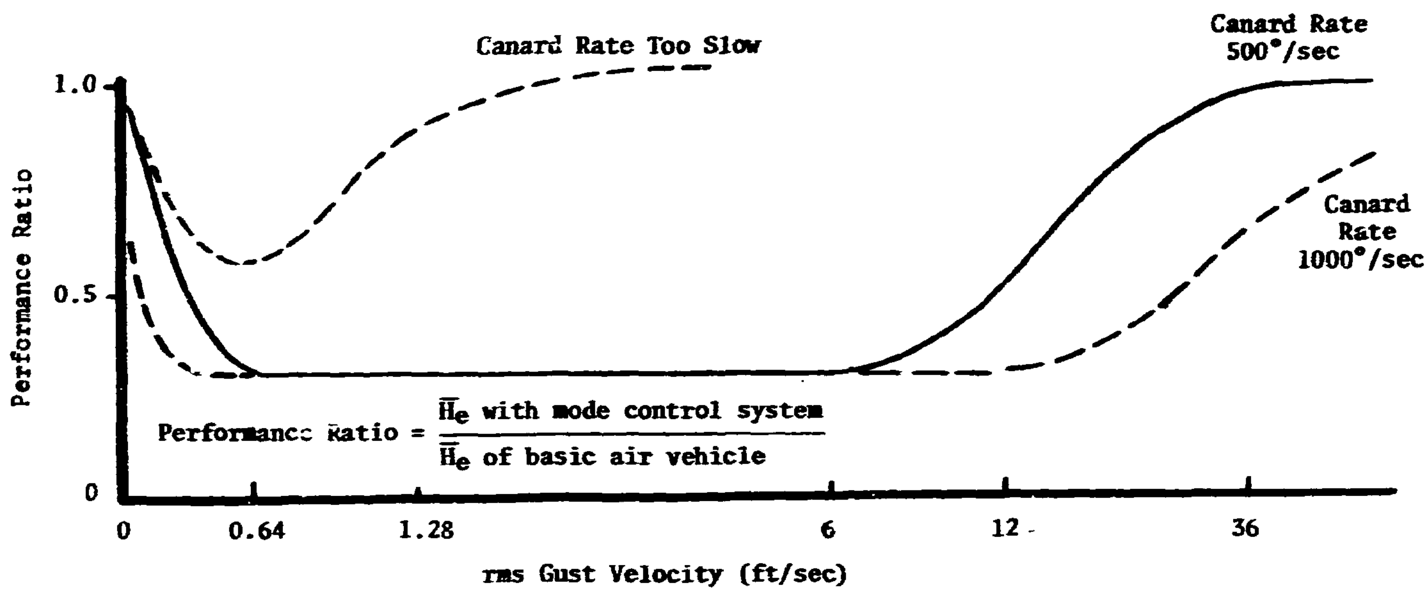


Figure 3 - SYSTEM PERFORMANCE AS FUNCTIONS OF GUST VELOCITY AND CANARD RATE

# SECTION III

# RIDE QUALITY CRITERIA EVALUATION

The objective of ride quality criteria is to achieve a satisfactory level of ride comfort over some given period of time. In the study of Reference 1, the aircraft was designed to a probability level so that the ride quality would be equal to or better than currently operating aircraft within the USAF inventory. The concept of a "probability of exceedance" is thus fundamental in determining an acceptable ride quality level. When we say the probability of exceedance of a given gust velocity, we mean that this is the probability that at a randomly selected instant, the actual gust is in excess of that gust value; it does not mean the probability that this gust value will be exceeded at some time during a given flight or a given number of flight hours. This probability can be envisioned as the fraction of gusts exceeding a given value out of all the gusts being considered. As such, it describes the proportion of total flight time spent in turbulence exceeding given values of gust velocity. Keep in mind, however, that this is based on averages for extended operating times.

Although this probability is not directly significant in determining an acceptable ride quality level, it does have an indirect significance. For two airplanes having the same gust environment, and allowing for the differences in the dynamic response, the ride quality levels can be compared for any given constant gust magnitude, or probability of exceedance. It was these considerations which influenced the choice of

an acceptable probability of exceedance.

Reference 1 approached the ride quality design criteria from the point of view of both a long and a short-time exposure tolerance. Under the proposed criteria, the ride quality design value was determined by either the long or the short-time value, whichever was more critical. Although this was not spelled out in detail, both criteria should be met. For airplanes without special mode control or gust alleviation systems, design to the most critical ride quality value would naturally meet the short-time as well as the long-time exposure criteria.

For airplanes having a gust or structural response alleviation system with varying performance, we can design to both criteria simultaneously. The allowable tolerance levels for long-time and short-time exposure can be used to define minimum system performance requirements. The short-time exposure limit is not very time dependent, but is rather a function of the magnitude of $\sigma_e$. In Reference 1, a short-time exposure of $\sigma_e=0.25$ was selected. This selection was based on the expected performance levels shown in Table I. The information given in Table I is plotted in Figure 4. The information breakdown of Table I and Figure 4 indicates that a more consistent separation point between the long-time and short-time exposure would be at $\sigma_u \bar{H}_e=0.28$ For this level of $\sigma_e$, the probability of exceedance should not be greater than 1%; for long-time exposure, the acceptable probability of exceedance remains at 20%.

## TABLE I

### CREW-MISSION PERFORMANCE LIMITATIONS

| $\sigma_u \overline{H}_e$ | Aircraft Acceptability | Mission Performance & Crew Effort | Physiological Effects |
|---|---|---|---|
| .07 | Acceptable for unlimited exposure time. | Mission performance not affected. | No effect on normal tasks. |
| .14 | Acceptable normal operation. | Mission performance adequate. | No effect on normal tasks, writing becomes difficult, small dials become difficult to read. |
| .21 | Acceptable normal operation not exceeding allowable exposure time. | Adequate for mission success; reasonable performance requires considerable crew concentration. | Normal tasks still possible. Manual control demands considerable attention and psychomotor coordination is reduced. Time to read instruments and displays and adjust controls increases. Small dials unreadable. Eventual setting in of fatigue. |
| .28 | Unsatisfactory for normal operations; unacceptable when exceeding allowable exposure times. | Adequate for mission success, but requires max. available pilot/crew concentration to achieve acceptable performance. | Limits of effective tracking. Manipulation of controls and other psychomotor tasks requires bracing of arms and legs and movements become deliberate. Pilot looks forward with only brief glances at instruments which cannot be read accurately. Cross checks are slowed down and tolerances widened. Rapid increase in fatigue. |
| .35 | Unacceptable except for emergency conditions. | Inadequate performance for mission success; aircraft controllable with minimum cockpit duties. | Beginning of unworkable level. Control of aircraft requires full pilot attention. Tasks other than stick and throttle control almost impossible. Pilot will establish hierarchy of tasks. Attention cannot be diverted from tracking task without immediate deterioration. |
| .42 | Unacceptable, dangerous. | Aircraft just controllable requiring max. pilot skill; mission success impaired. | Performance levels low and all tasks impossible except for gross adjustments. Displays difficult if not impossible to read. Concern for structural integrity. |

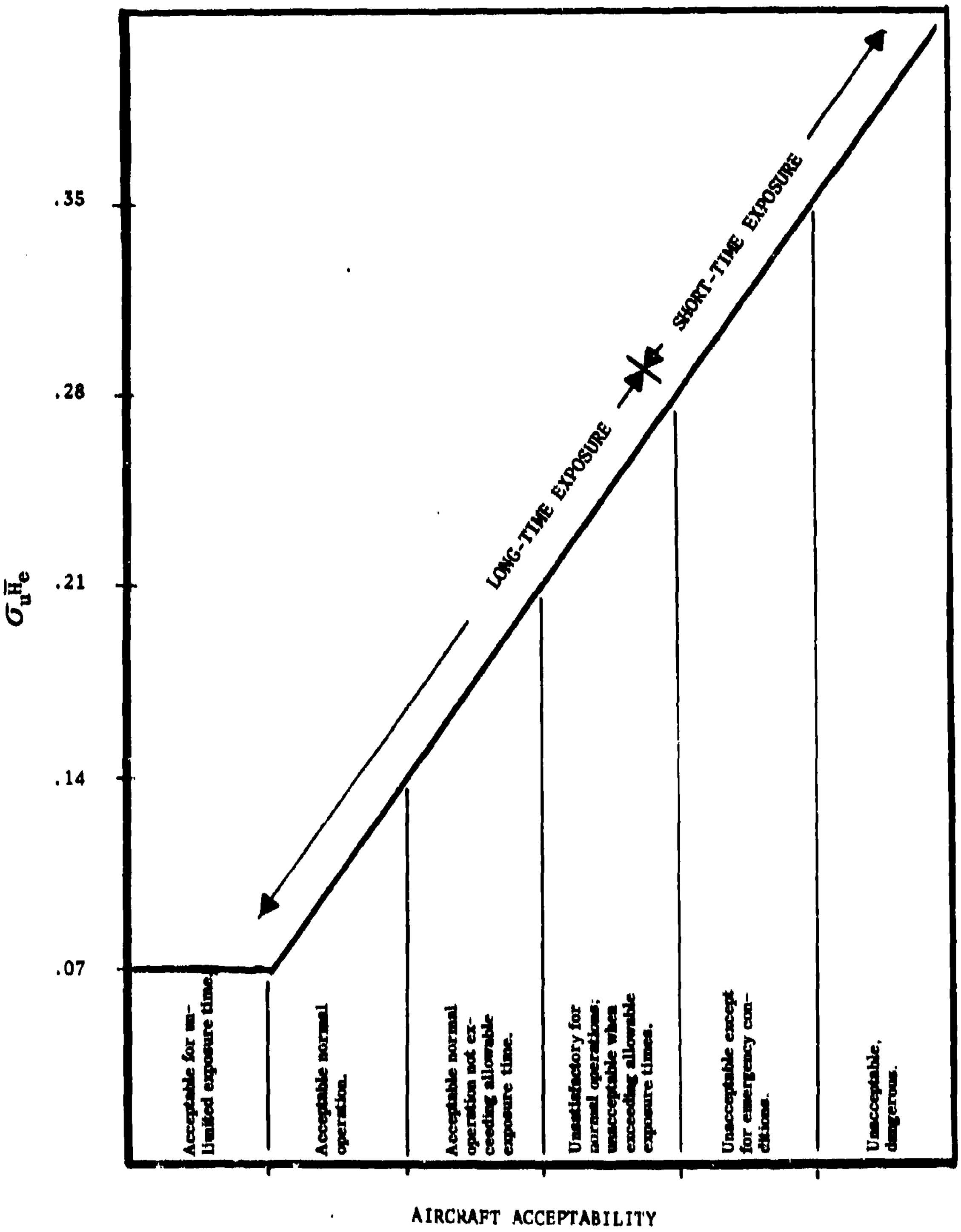


Figure 4 - CREW-MISSION PERFORMANCE LIMITATIONS

Reference 6 presents a rough indication of pilot opinion about vibration levels. A pilot rating of negligible is given for rms acceleration values less than 0.05 rms "g". An average $\overline{H}_e/\overline{A}$ value of 1.22 as derived from Table IV of Reference 1, gives a $\sigma_e$ value of 0.062, which agrees quite reasonably with the value of $\sigma_e = 0.07$ given in Table VI of Reference 1 as acceptable for unlimited exposure time. A value of $\overline{H}_e = \frac{0.07}{\sigma_u}$ is suggested as the limit for low-gust magnitudes, where system nonlinear deadband, hysteresis, and preload problems exist.

To determine the design goals for the lateral mode control system, we can again use the approach of Reference 1. The values of $\overline{H}_{e_V}$ are plotted on line "a" of Figure 5, and the required values of $\overline{H}_{e_L}$ are the corresponding values on the abscissa. The lateral ride quality values, however, must be met with lateral gust velocity inputs at the same probability levels as specified for the vertical gust velocities.

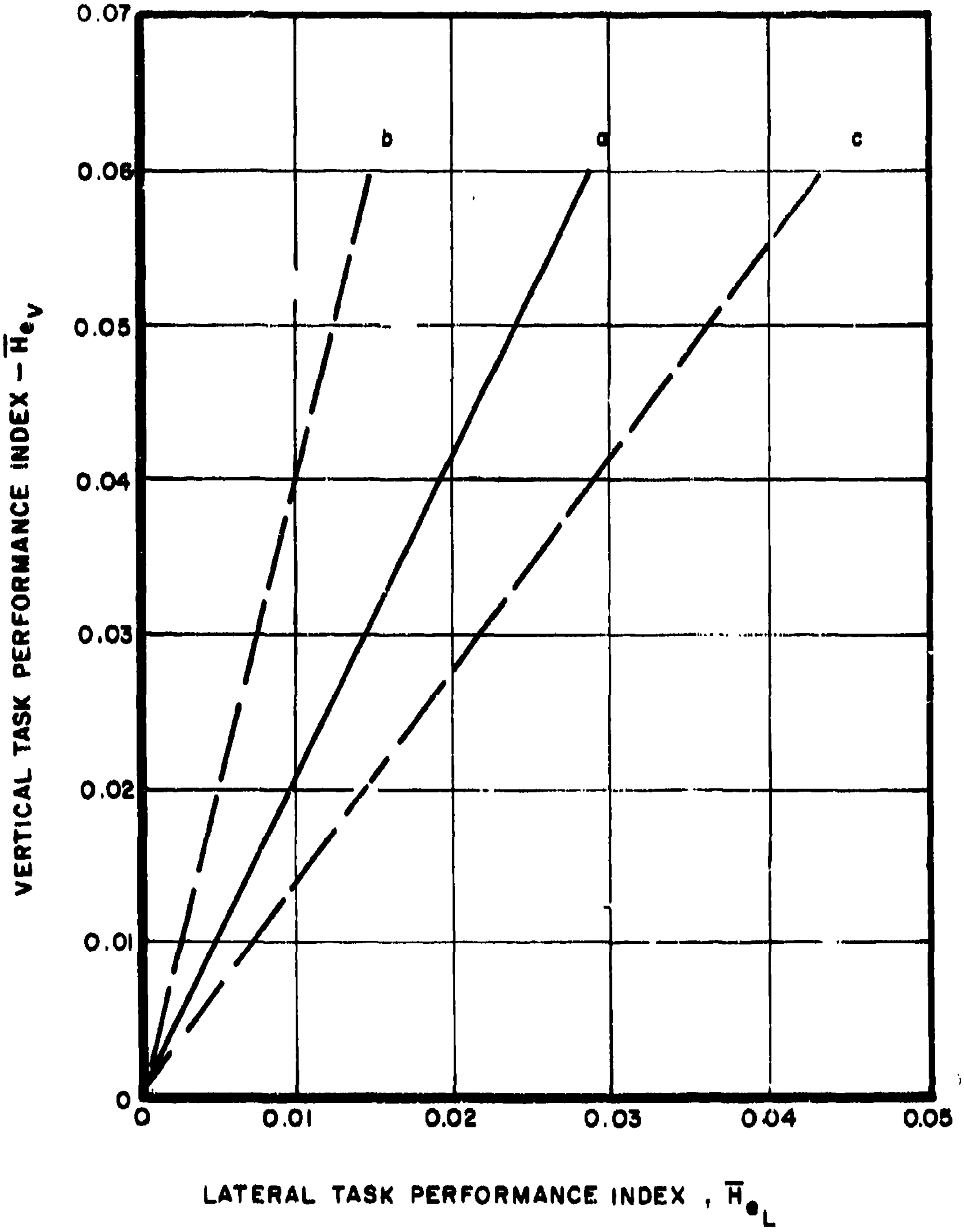


Figure 5 - Variability of Vertical and Lateral Task Performance Index

# SECTION IV

## MODE CONTROL SYSTEM CONSIDERATIONS

Under the ride quality criteria defined for an aircraft employing an active mode control system, the values for the vertical and lateral ride quality are considered to be independent. In other words, the criteria thus far developed are based on the idea that the ride comfort or performance is influenced by either the vertical gust or the lateral gust, and that any mode control system incorporates two separate systems, one for the vertical and one for the lateral response.

In the case where separate vertical and lateral systems are provided, each system would exhibit the typical performance degradation with gust velocity shown in Figure 6. Yet ride quality is known to be affected by simultaneous vertical and lateral vibration. The overall performance of two independent ride control systems in meeting required ride quality levels, thus must be based on vertical and lateral turbulence occurring simultaneously. This performance requirement can be represented by an envelope of vertical versus lateral gust velocities which would demand peak power rates no higher than power available. Such an envelope is presented in Figure 7. The shaded area of Figure 7 represents the region of full system performance. Any combination of gust velocities within this area can be met without exceeding available rates and/or deflection of either system.

The gust envelope for a single mode control system designed to improve the ride quality in both vertical and lateral directions will be of the

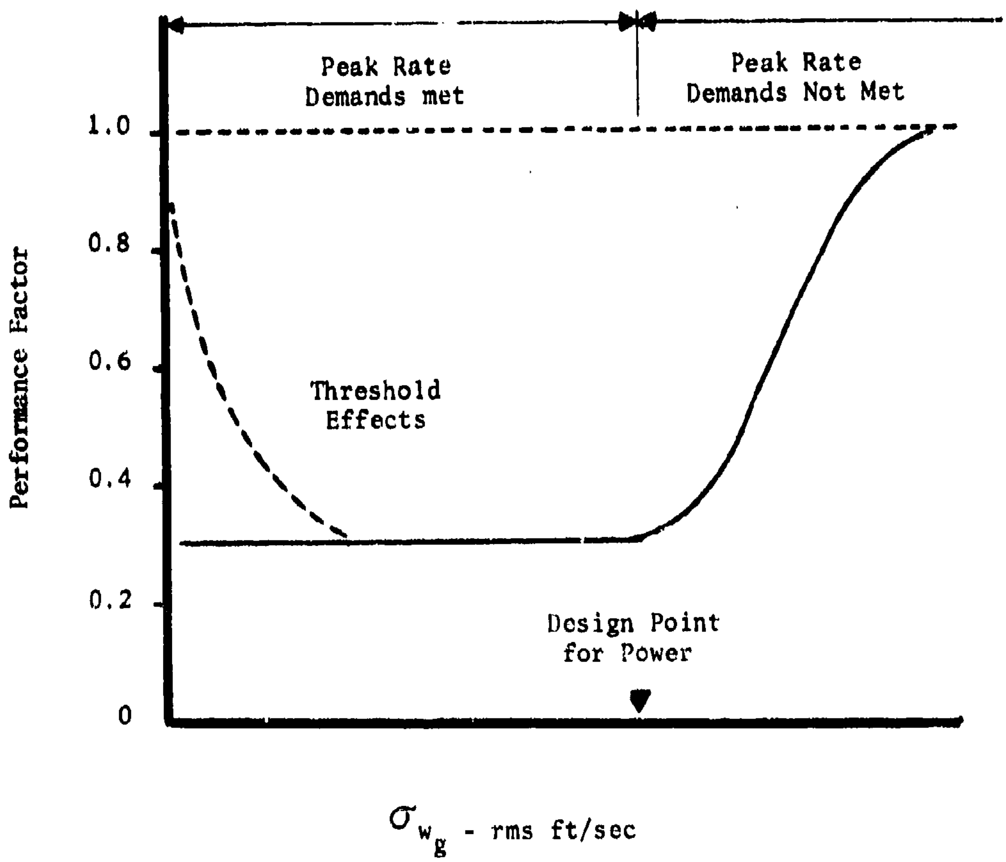


Figure 6 - TYPICAL EFFECTS OF POWER LIMITS AND DEFLECTION THRESHOLD ON SYSTEM PERFORMANCE

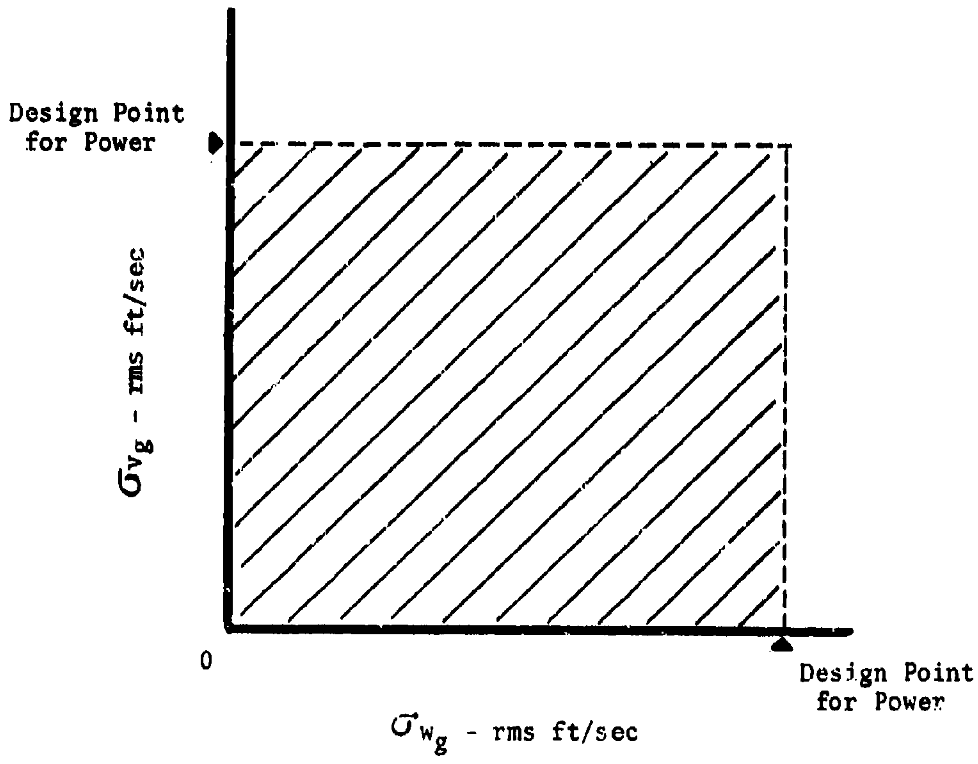


Figure 7 - TYPICAL GUST VELOCITY ENVELOPE BASED ON SEPARATE VERTICAL AND LATERAL SYSTEM PERFORMANCE

shape shown in Figure 8. The shaded area represents the region of full performance.

The question is how the design gust envelope for a single vertical-lateral mode control system may be determined from the criteria for separate vertical and lateral ride quality. It is obvious that for consistent design criteria, the probability of full system performance without saturation should be identical for both cases.

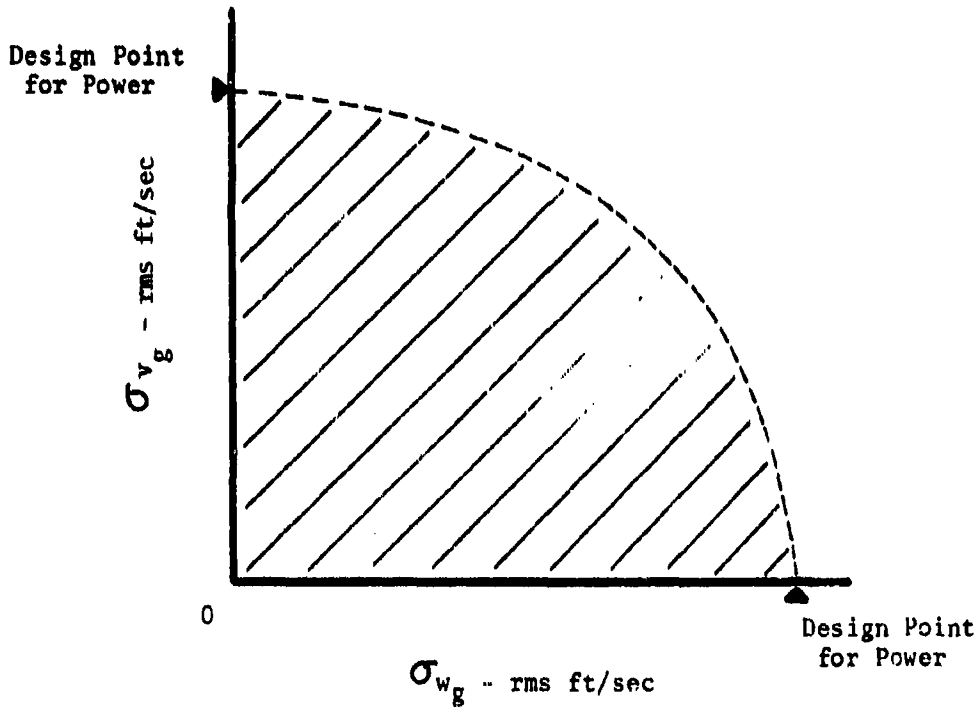


Figure 8 - TYPICAL GUST VELOCITY ENVELOPE BASED ON SINGLE SYSTEM PERFORMANCE

# SECTION V

## APPLICATION OF SYSTEM DESIGN CRITERIA

Consider that the mode control system as a whole (vertical and lateral) responds to structural motions caused by varying combinations of vertical and lateral gust inputs. The probability density functions for these two gust inputs are assumed known.

For the sake of consistency with earlier work as well as with the MIL-A-008861A specification, let us consider the von Karman power spectrum and turbulence field parameters of Reference 5 as presented in Table II. The suggested expression for the probability density function is:

$$f(\sigma_u) = \frac{P_1}{b_1}\sqrt{\frac{2}{\pi}}\, e^{-\sigma_u^2/2b_1^2} + \frac{P_2}{b_2}\sqrt{\frac{2}{\pi}}\, e^{-\sigma_u^2/2b_2^2} \quad (1)$$

The cumulative probability distribution is obtained by integrating the probability density functions:

$$F(\sigma_u) = \int_0^{\sigma_u} f(\sigma_u)\, d\sigma_u \quad (2)$$

The probability that the value $\sigma_u$ is between $\sigma_{u_1}$ and $\sigma_{u_2}$ is then determined by:

$$F(\sigma_{u_1}, \sigma_{u_2}) = \int_{\sigma_{u_1}}^{\sigma_{u_2}} f(\sigma_u)\, d\sigma_u \quad (3)$$

TABLE II

TURBULENCE FIELD PARAMETERS

| MISSION SEGMENT | ALTITUDE | DIRECTION | $P_1$ | $b_1$ | $P_2$ | $b_2$ | L(ft) |
|---|---|---|---|---|---|---|---|
| Low-Level Contour | 0- 1000 ft | Vertical | 1.0 | 2.7 | $10^{-5}$ | 10.65 | 500 |
| Low-Level Contour | 0- 1000 ft | Lateral | 1.0 | 3.1 | $10^{-5}$ | 14.06 | 500 |
| Climb, Cruise, Descent | 0- 1000 ft | Vert. & Lat. | 1.0 | 2.51 | 0.005 | 5.04 | 500 |
| Climb, Cruise, Descent | 1,000- 2,500 ft | Vert. & Lat. | 0.42 | 3.02 | 0.0033 | 5.94 | 1750 |
| Climb, Cruise, Descent | 2,500- 5,000 ft | Vert. & Lat. | 0.30 | 3.42 | 0.0020 | 8.17 | 2500 |
| Climb, Cruise, Descent | 5,000-10,000 ft | Vert. & Lat. | 0.15 | 3.59 | 0.00095 | 9.22 | 2500 |
| Climb, Cruise, Descent | 10,000-20,000 ft | Vert. & Lat. | 0.062 | 3.27 | 0.00028 | 10.52 | 2500 |
| Climb, Cruise, Descent | 20,000-30,000 ft | Vert. & Lat. | 0.025 | 3.15 | 0.00011 | 11.88 | 2500 |
| Climb, Cruise, Descent | 30,000-40,000 ft | Vert. & Lat. | 0.011 | 2.93 | 0.000095 | 9.84 | 2500 |
| Climb, Cruise, Descent | 40,000-50,000 ft | Vert. & Lat. | 0.0046 | 3.28 | 0.000115 | 8.81 | 2500 |
| Climb, Cruise, Descent | 50,000-60,000 ft | Vert. & Lat. | 0.002 | 3.82 | 0.000078 | 7.04 | 2500 |
| Climb, Cruise, Descent | 60,000-70,000 ft | Vert. & Lat. | 0.00088 | 2.93 | 0.000057 | 4.33 | 2500 |

For small values of $\Delta\sigma_u = \sigma_{u_1} - \sigma_{u_2}$, this probability can be denoted by:

$$F(\sigma_{u_1}, \sigma_{u_2}) \quad f(\sigma_{u_1}, \sigma_{u_2})\Delta\sigma_u \qquad (4)$$

where $f(\sigma_{u1}, \sigma_{u2})$ is the average probability density values for the increment $\sigma_{u1} - \sigma_{u2}$. Typical probability density functions based on Equation 1 are shown in Figure 9. Figure 10 presents the associated cumulative probabilities.

First, it is necessary to determine the combination of gust velocity levels for which a vertical and lateral mode control system should be designed. Based on considerations presented in Section IV, gust velocity magnitudes of 7 fps and 8 fps for the vertical and lateral gust inputs, respectively, are indicated. It now becomes possible to determine the probability of having full system performance in both axes. The probability of being in the shaded area of either Figure 7 or 8 can be found by summing the probabilities of $\sigma_{v_g}$ and $\sigma_{w_g}$ being jointly in particular intervals within the envelope.

It is possible to consider an infinite number of gust velocity combinations. From a practical viewpoint, the number of conditions to which the system is to be designed must be a manageable number. This can be accomplished by dividing the probability density curve into a reasonable number of finite intervals and treating these intervals as discrete probabilites. As shown in Figure 11, this procedure might result in

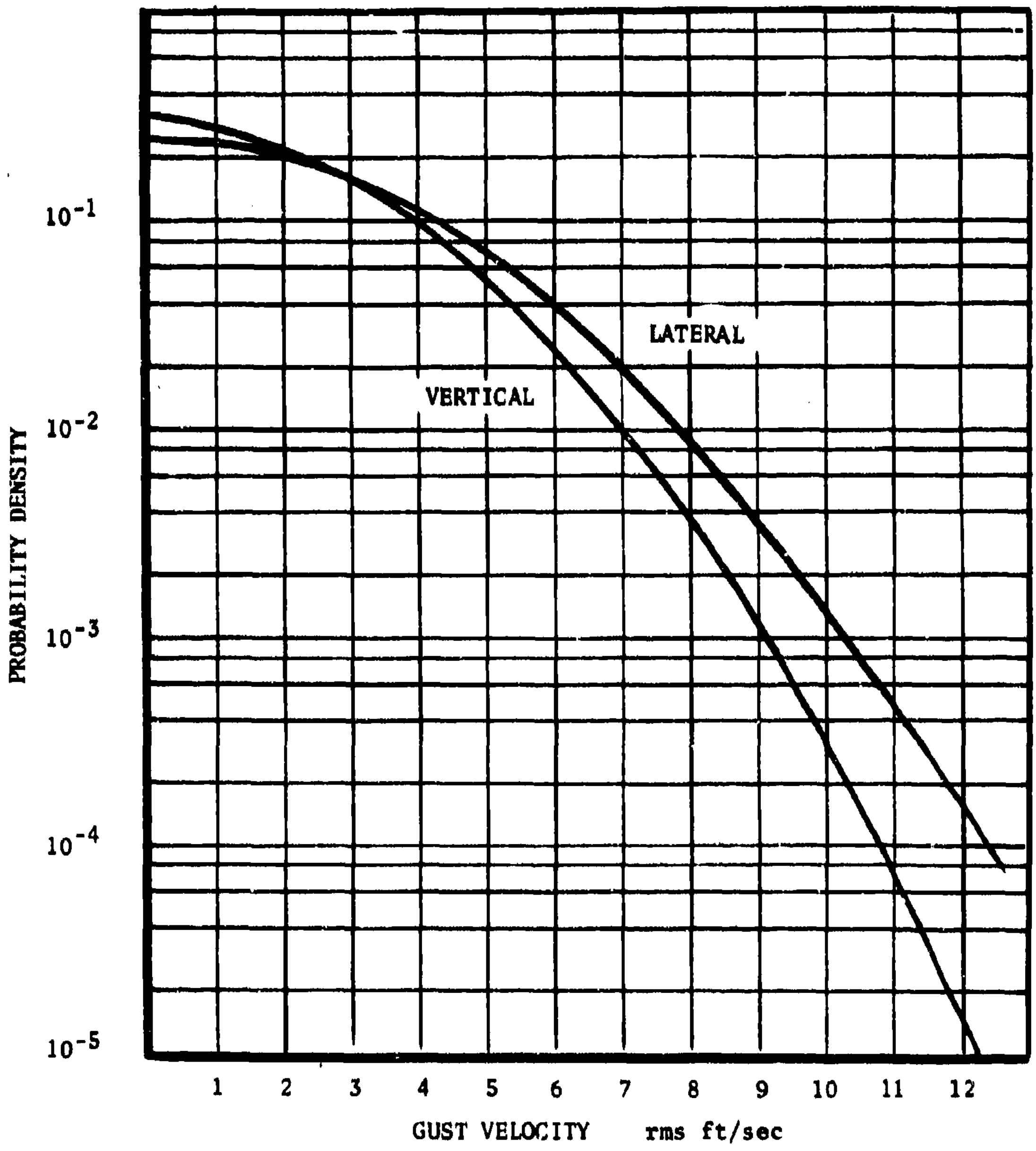


Figure 9 - PROBABILITY DENSITY OF GUST VELOCITY

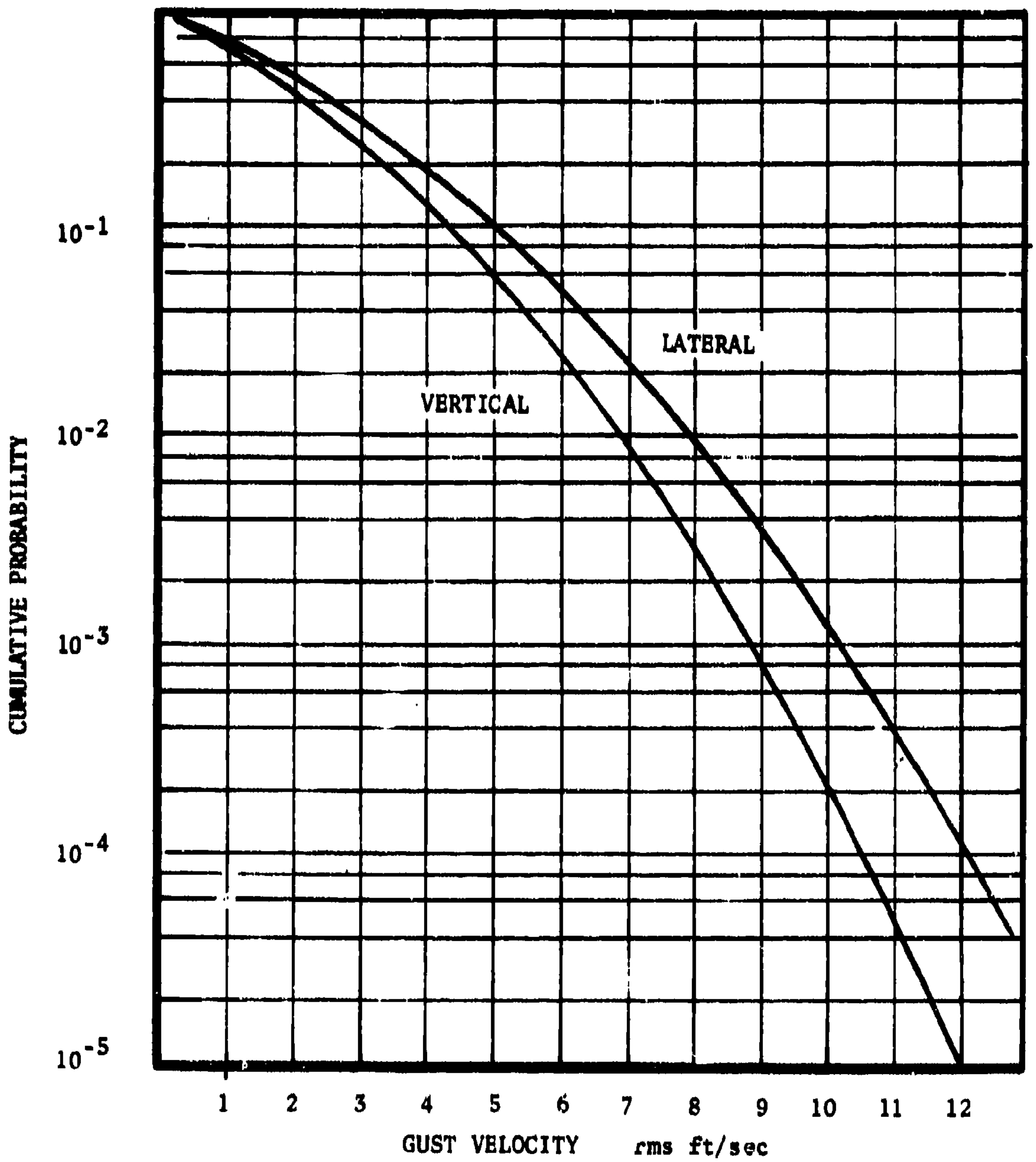


Figure 10 - PROBABILITY OF EXCEEDING GUST VELOCITY

increments of 1 fps. For statistically independent parameters, the probability of simultaneous occurrence of two parameters A and B, is equal to the probability of A times the probability of B.

$$P(A,B) = P(A) \times P(B)$$

Within any constant intensity patch of turbulence, the vertical and lateral components of the turbulence can be presumed to be uncorrelated. Indeed, the three components of LO-LOCAT gust velocity samples have supported this hypothesis.

Using the above considerations for the gust envelope of Figure 12, gust velocity intervals and their associated joint probabilities were determined and are presented in Table III. Designing to the conditions of Table III is considered to provide a system for the envelope shown in Figure 12 which is capable of meeting the requirements at the probability level of 0.9814.

The probability of deterioration in the system's performance is expressed by the area outside the envelope and would be

$$1 - 0.9814 = 0.0186$$

If a single system is used to meet the same gust velocities, the probability of system saturation would be increased. Table IV shows that for the same gust velocity criteria, this probability would be $1 - 0.9655 = 0.0345$, or almost double.

In order to ascribe equal importance in defining system performance

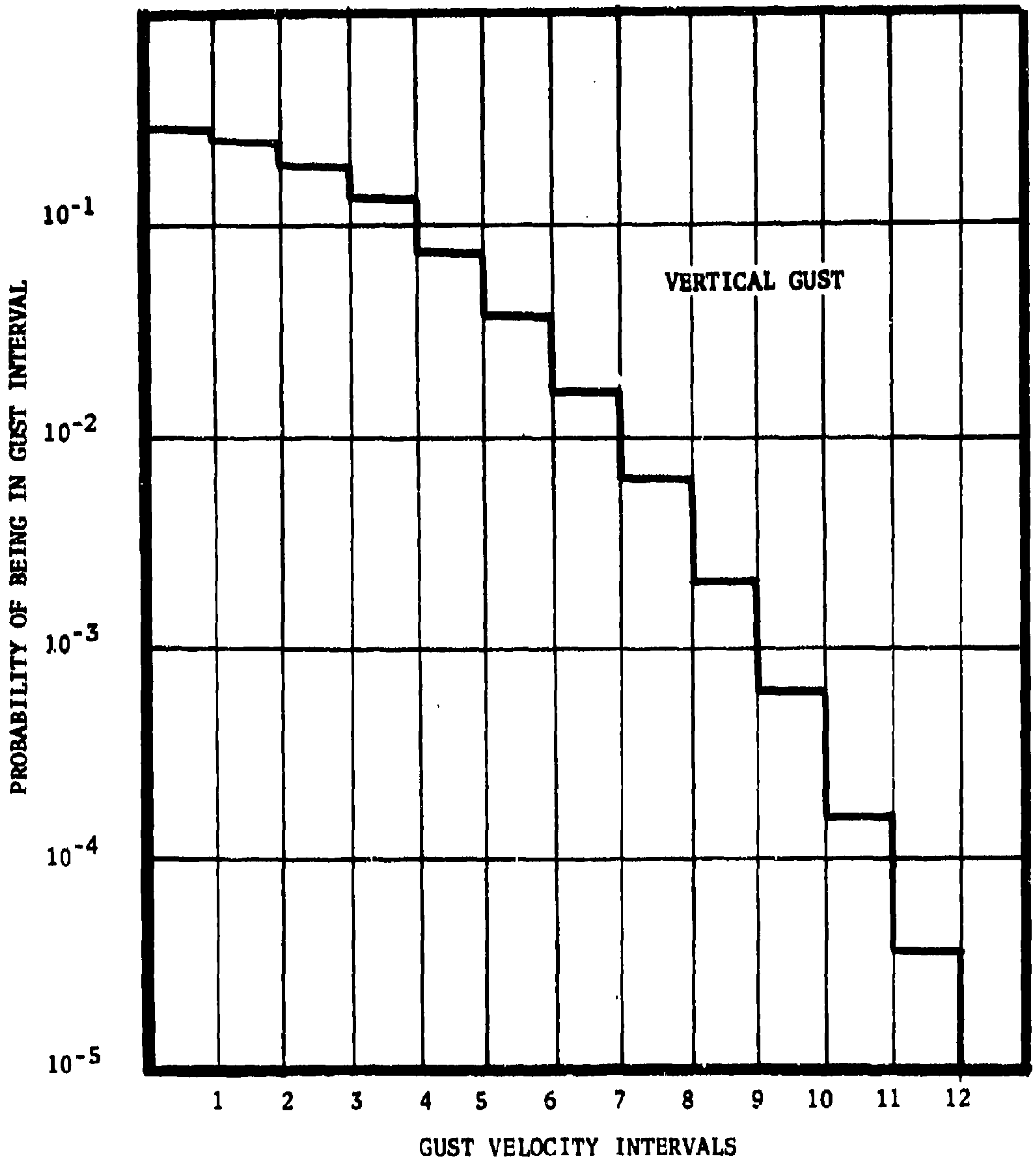


Figure 11 - PROBABILITY OF BEING IN GUST INTERVAL

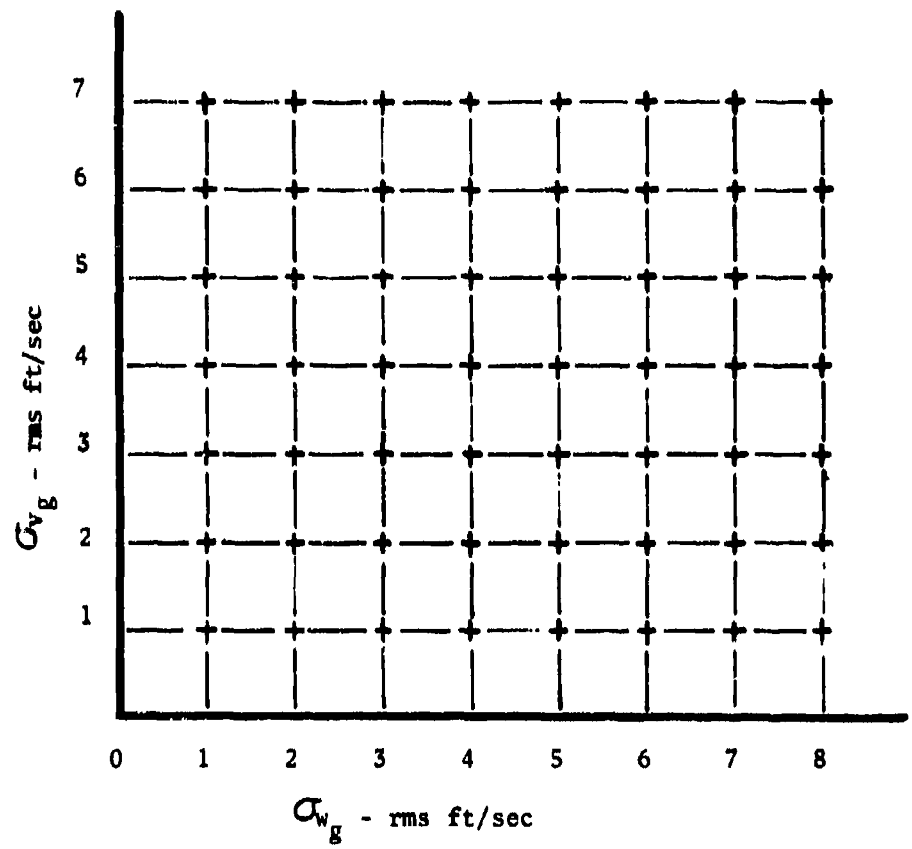


Figure 12 - COMBINED VERTICAL AND LATERAL GUST ENVELOPE FOR A DOUBLE SYSTEM

TABLE III

JOINT PROBABILITIES FOR VERTICAL AND LATERAL GUST VELOCITY INTERVALS (SEPARATE SYSTEMS)

| Vertical Gust Velocity Intervals | Lateral Gust Velocity Intervals 0-1 | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 |
|---|---|---|---|---|---|---|---|---|
| 0-1 | .073798 | .066504 | .054010 | .039526 | .026070 | .015494 | .008299 | .004005 |
| 1-2 | .064339 | .057979 | .047086 | .034459 | .022728 | .013508 | .007241 | .003492 |
| 2-3 | .048902 | .044068 | .035789 | .026192 | .017275 | .010267 | .005499 | .002654 |
| 3-4 | .032404 | .029201 | .023715 | .017355 | .011446 | .006803 | .003643 | .001758 |
| 4-5 | .018720 | .016869 | .013700 | .010026 | .006613 | .003930 | .002105 | .001016 |
| 5-6 | .009428 | .008496 | .006900 | .005049 | .003330 | .001979 | .001060 | .000511 |
| 6-7 | .004139 | .003730 | .005029 | .002217 | .001462 | .000869 | .000465 | .000224 |

Summation of Joint Probabilities = .9814

## TABLE IV

### JOINT PROBABILITIES FOR VERTICAL AND LATERAL GUST VELOCITY INTERVALS FOR A SINGLE SYSTEM BASED ON SEPARATE SYSTEM GUST VELOCITY CRITERIA

| Vertical Gust Velocity Intervals | Lateral Gust Velocity Intervals | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0-1 | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 |
| 0-1 | .073798 | .066504 | .054010 | .039526 | .026070 | .015494 | .008299 | .004005 |
| 1-2 | .064339 | .057979 | .047086 | .034459 | .022728 | .013508 | .007241 | .003492 |
| 2-3 | .048902 | .044068 | .035789 | .026192 | .017275 | .010267 | .005499 | .001636 |
| 3-4 | .032404 | .029201 | .023715 | .017355 | .011446 | .006803 | .003643 | |
| 4-5 | .018720 | .016869 | .013700 | .010026 | .006613 | .003930 | | |
| 5-6 | .009428 | .008496 | .006900 | .005049 | .003330 | | | |
| 6-7 | .004139 | .003730 | .001859 | | | | | |

Summation of Joint Probabilities = .9655

regardless of whether a single or multiple system is used, it is necessary that the design be based on equal probability levels. A trial and error process of the method produced the gust envelope of Figure 13 for the single vertical-lateral mode control system.

The joint probabilities of the vertical and lateral gust increments are presented in Table V. As can be seen, the gust velocities within the envelope of Figure 13 provide a probability of full system performance approximately equal to that obtained from two separate systems, or

$$1 - 0.9816 = 0.0184$$

In the trial and error method, the lateral and vertical gust velocities were increased simultaneously based on equal cumulative probability levels. This approach may not be absolutely necessary in view of the fact that the total vertical and lateral ride quality is of importance. Presumably in such a case either vertical or lateral or both gust inputs can be changed any amount necessary to meet the probability goal set by the separate systems. However, until the real relationship between vertical and lateral ride quality is more definitely established, it seems appropriate to retai the levels derived from Figure 5.

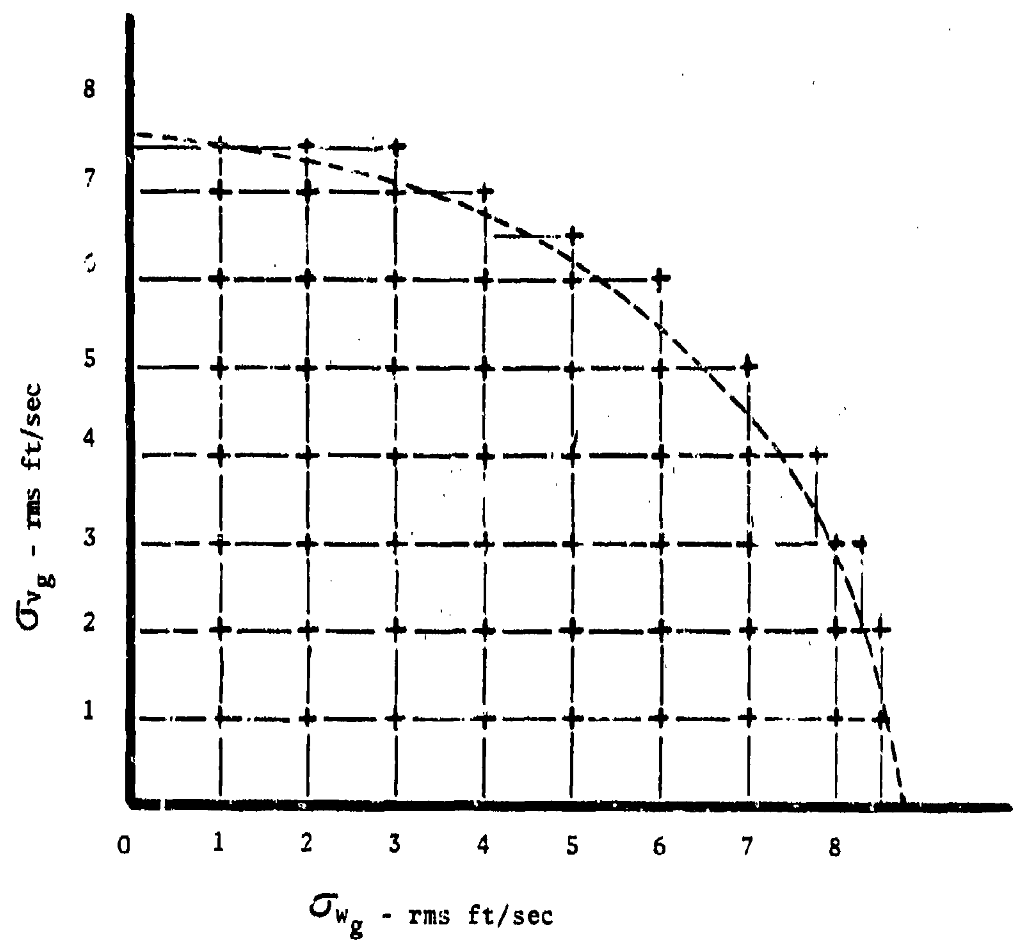


Figure 13 - COMBINED VERTICAL AND LATERAL GUST ENVELOPE FOR A SINGLE SYSTEM

TABLE V

JOINT PROBABILITIES FOR VERTICAL AND LATERAL GUST VELOCITY INTERVALS FOR A SINGLE SYSTEM BASED ON SINGLE SYSTEM GUST VELOCITY CRITERIA

| Vertical Gust Velocity Intervals | Lateral Gust Velocity Intervals | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0-1 | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-L |
| 0-1 | .073798 | .066504 | .054010 | .039526 | .026070 | .015494 | .008299 | .004005 | .001118 |
| 1-2 | .064339 | .057979 | .047086 | .034459 | .022728 | .013508 | .007241 | .003492 | .000975 |
| 2-3 | .048902 | .044068 | .035789 | .026192 | .017275 | .010267 | .005499 | .002654 | .000404 |
| 3-4 | .032404 | .029201 | .023715 | .017355 | .011446 | .006803 | .003643 | .001483 | |
| 4-5 | .018720 | .016869 | .013700 | .010026 | .006613 | .003930 | .002105 | | |
| 5-6 | .009428 | .008496 | .006900 | .005049 | .003330 | .001979 | | | |
| 6-7 | .004139 | .003730 | .003029 | .002217 | .000897 | | | | |
| 7-L | .001016 | .000915 | .000743 | | | | | | |

Summation of Joint Probabilities = .9816

# SECTION VI

## CONCLUSIONS AND RECOMMENDATIONS

The ride quality criteria of Reference 1 were expanded to include aircraft with active mode control systems. The new criteria provide a means for specifying minimum acceptable mode control system performance.

Designing double and single mode control systems to identical gust velocities will result in different probabilities of system saturation. An approach has been presented which allows determination of gust velocities which should be used in the design of single mode control systems.

The problem of system failure has not been discussed. It is clear that for a multiple mode control system, failure in one axis would still provide improved ride quality in the other. In a single system, however, failure results in loss of ride quality improvement in both axes simultaneously. In that case, the ride quality would be equal to that available for the basic vehicle. This would indicate that reliability for the single system should be better than that for a multiple system by some undetermined amount.

On the whole, the following design considerations are suggested for airplane ride quality:

1. Vertical Gust Inputs
   a. A value of $\sigma_e = 0.07$ shall not be exceeded at low gust magnitudes.
   b. The probability of exceedance for long-time exposure shall not be greater than 20%.

c. For short-time exposure, the probability of exceedance of the value $\sigma_e = 0.28$ shall not be greater than 1.0%.

2. Lateral Gust Inputs

a. The corresponding values for $\overline{H}_{e_L}$ can be determined from Figure 5, line "a".

b. The lateral $\overline{H}_e$ values should be met with lateral gust velocity inputs at the same probability levels specified for the vertical.

3. Combined Vertical and Lateral Gusts

a. For separate mode control systems in both axes, the criteria of 1 and 2 above apply directly.

b. For a single mode control system which affects both axes, the gust velocity values from 1 and 2 should be increased so that the overall probability of system saturation is no greater than that for two separate systems.

# APPENDIX

## SAMPLE PROBLEM

The mission of an airplane requires flight at sea level for a duration of 150 minutes.

a. Figure 14 shows for T=150 minutes, $\sigma_e = 0.11$.

b. For a cumulative probability level of 0.2, Figure 15 shows a vertical rms gust velocity of 3.5 fps.

c. For a cumulative probability level of 0.11, Figure 15 indicates a vertical gust value of 7 fps rms and a lateral gust value of 8 fps rms.

d. Long-time exposure $\overline{H}_{e_V} = .11/3.5 = 0.0314$.

e. Short-time exposure $\overline{H}_{e_V} = .28/7 = 0.04$.

f. From Figure 16, for $\overline{H}_{e_V} = 0.0314$ long-time exposure $\overline{H}_{e_L} = 0.015$.

g. From Figure 16, for $\overline{H}_{e_V} = 0.04$ short-time exposure $\overline{H}_{e_L} = 0.019$.

h. For low gust magnitudes, $\sigma_{e_V} = 0.07$ shall not be exceeded.

i. From Figure 16, for $\sigma_{e_V} = 0.07$ a lateral $\sigma_{e_L}$ value is 0.0335.

j. Figure 17 gives for the minimum acceptable ride quality levels for the airplane with or without active mode control systems.

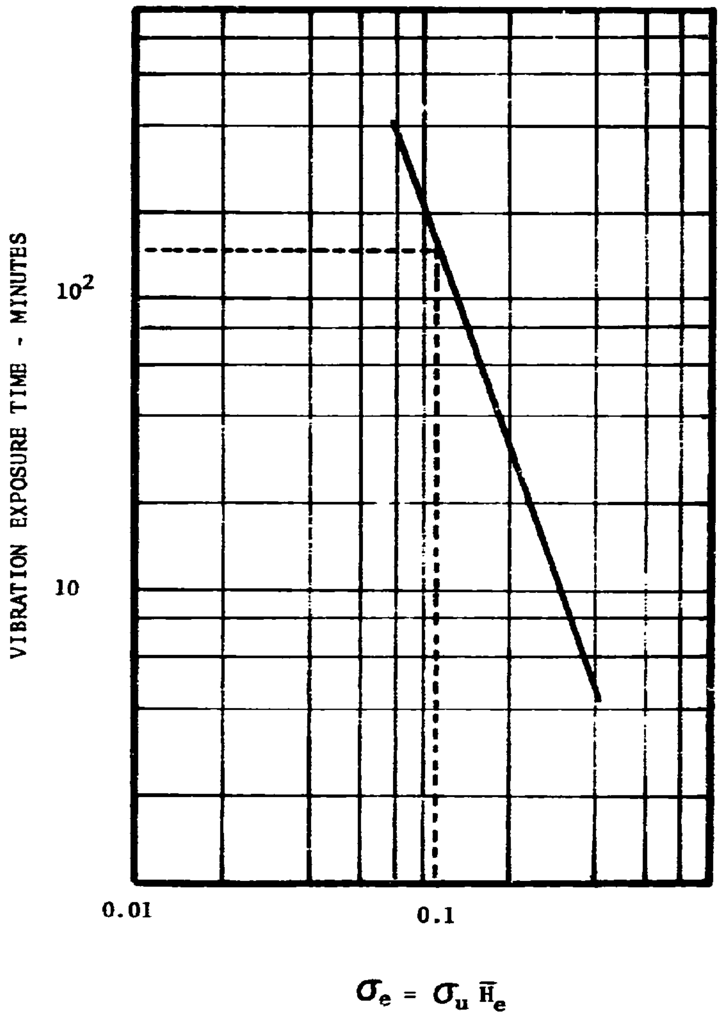


Figure 14 - EXPOSURE TIME AS A FUNCTION OF RMS CREW TASK ERROR RESPONSE FOR VERTICAL VIBRATION

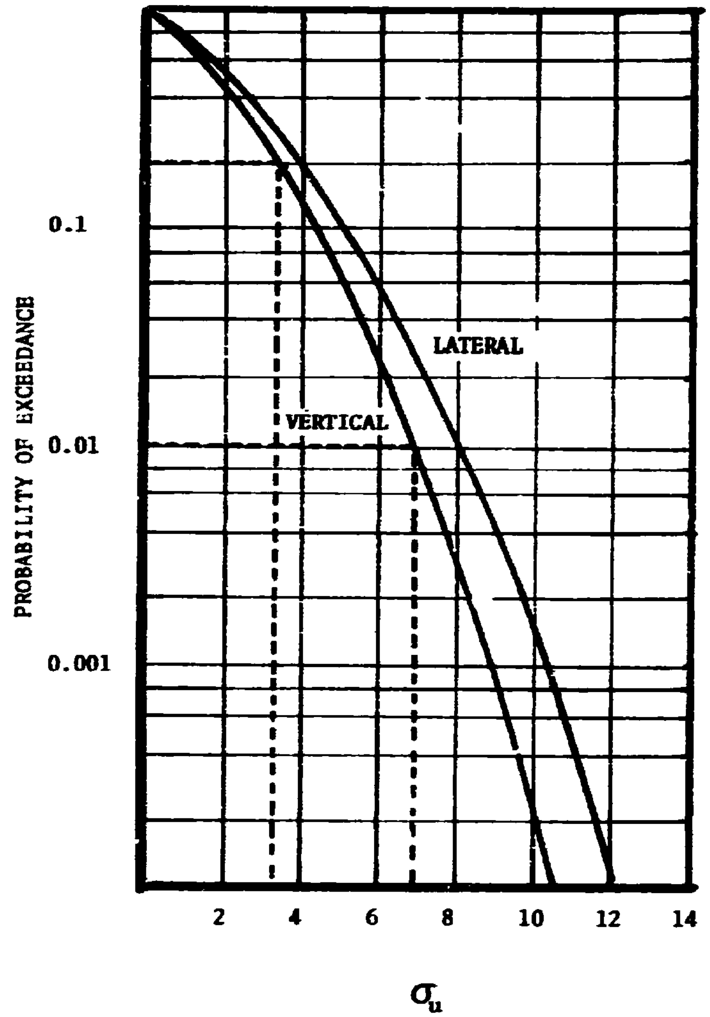


Figure 15 - PROBABILITY OF EXCEEDING GUST VELOCITY

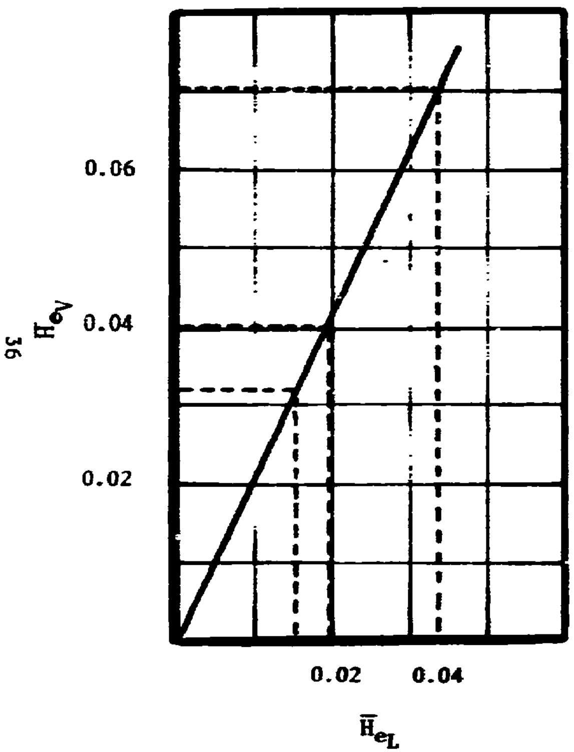


Figure 16 - VERTICAL TO LATERAL TASK PERFORMANCE INDEX RELATIONSHIP

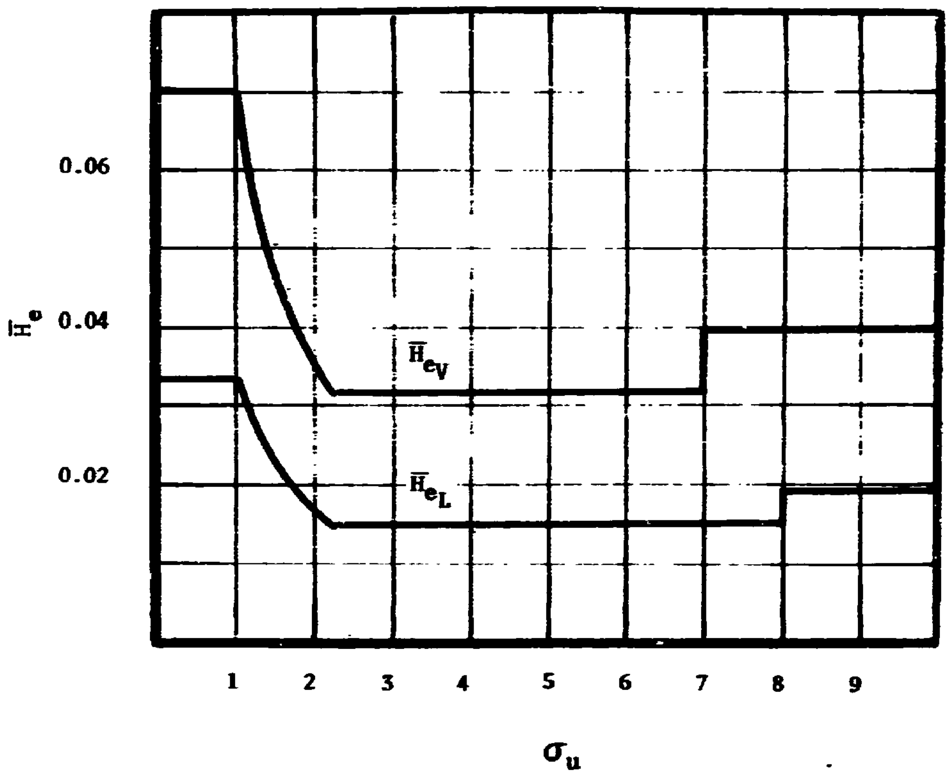


Figure 17 - RIDE QUALITY DESIGN LEVELS FOR SAMPLE PROBLEM AIRPLANE

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